

*Presentation for the  
Global Solar and Wind Resource  
Assessment Project*

**Wind Resource Assessment and  
Mapping at the U.S. National  
Renewable Energy Laboratory**

Dennis Elliott  
NREL, Principal Scientist

# *Outline of Presentation*

- Introduction and rationale for wind mapping
- UNEP wind mapping project activities
- Examples of NREL's high-resolution wind maps
  - Developing country - Philippines Atlas
  - Wind Powering America - North Dakota
- NREL's GIS-based wind mapping system
  - Logic of mapping system and required inputs
  - Data sets and analysis procedures
  - Outputs of mapping system
- Conclusions

# *Rationale for Wind Resource Assessment and Mapping*

The lack of reliable and detailed wind energy resource maps and data is a significant impediment to large-scale use of wind energy technologies, particularly in the developing world.

# *UNEP Project Activities for High-Resolution (1-km) Wind Mapping*

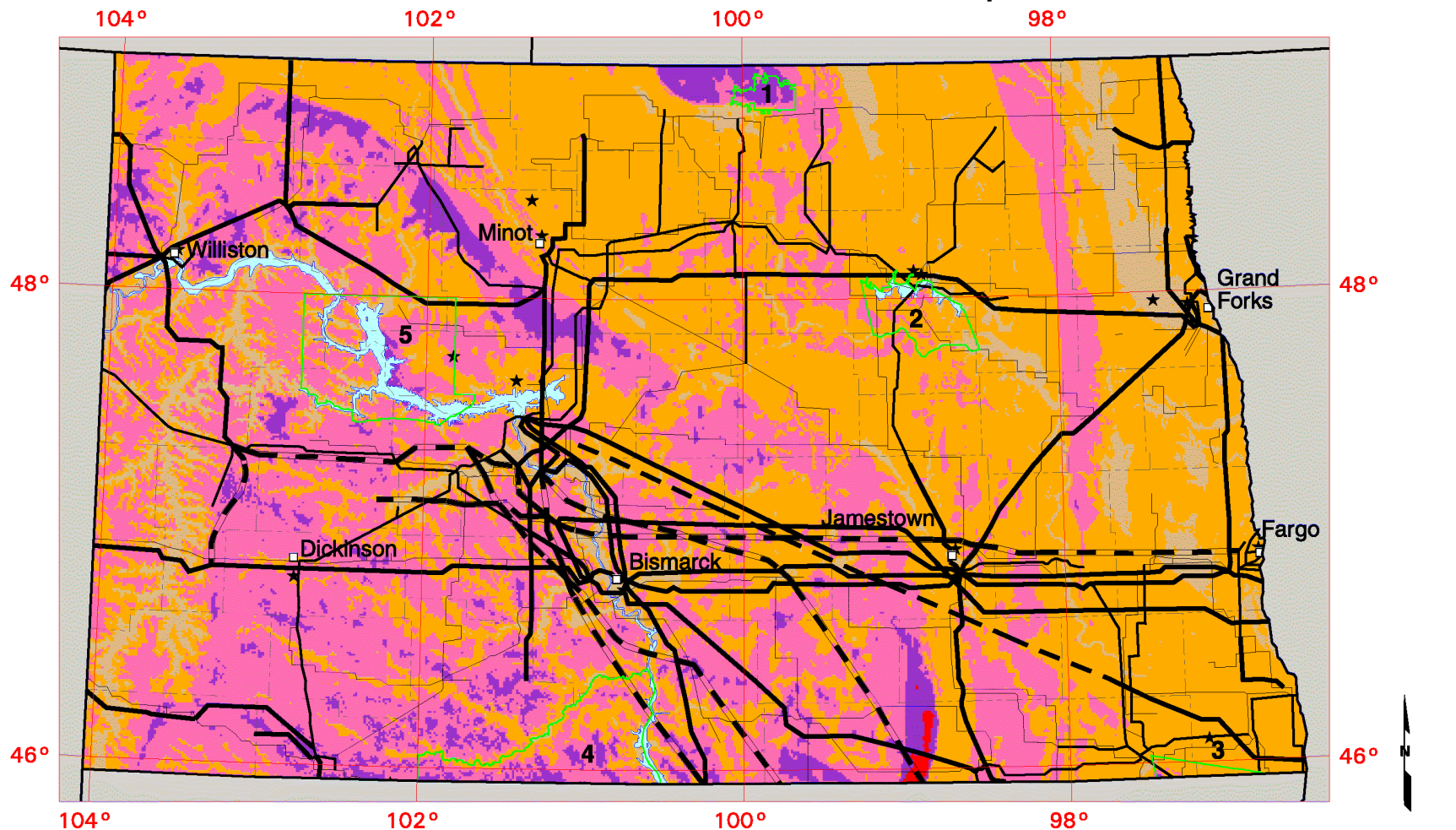
- Review previous surveys
- Identify and obtain existing wind and other meteorological data
  - NREL's global database
  - Host country data
- Process and analyze data
- Develop wind resource maps and other products using NREL's GIS-based mapping system
- Produce wind resource atlas

# *UNEP Project Deliverables for Regional Wind Mapping*

- High resolution (1-km) wind maps, elevation maps, and political maps
- Wind resource atlas with maps and summaries of salient wind characteristics (e.g. seasonal/monthly, diurnal, interannual, direction frequency, etc.)
- Maps and atlas on CD-ROM

# *NREL's State-of-the-art High Resolution (1km) Wind Resource Maps*

# North Dakota - Wind Resource Map



## Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m <sup>2</sup>	Wind Speed <sup>a</sup> at 50 m m/s	Wind Speed <sup>a</sup> at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7

<sup>a</sup>Wind speeds are based on a Weibull k value of 2.0

★ Meteorological Station with Wind Data  
□ City or Town

## Transmission Line Voltage

- 69 Kilovolts
- - - 115 Kilovolts
- . - 230 Kilovolts
- 345 Kilovolts
- - - Under Construction

## Indian Reservations

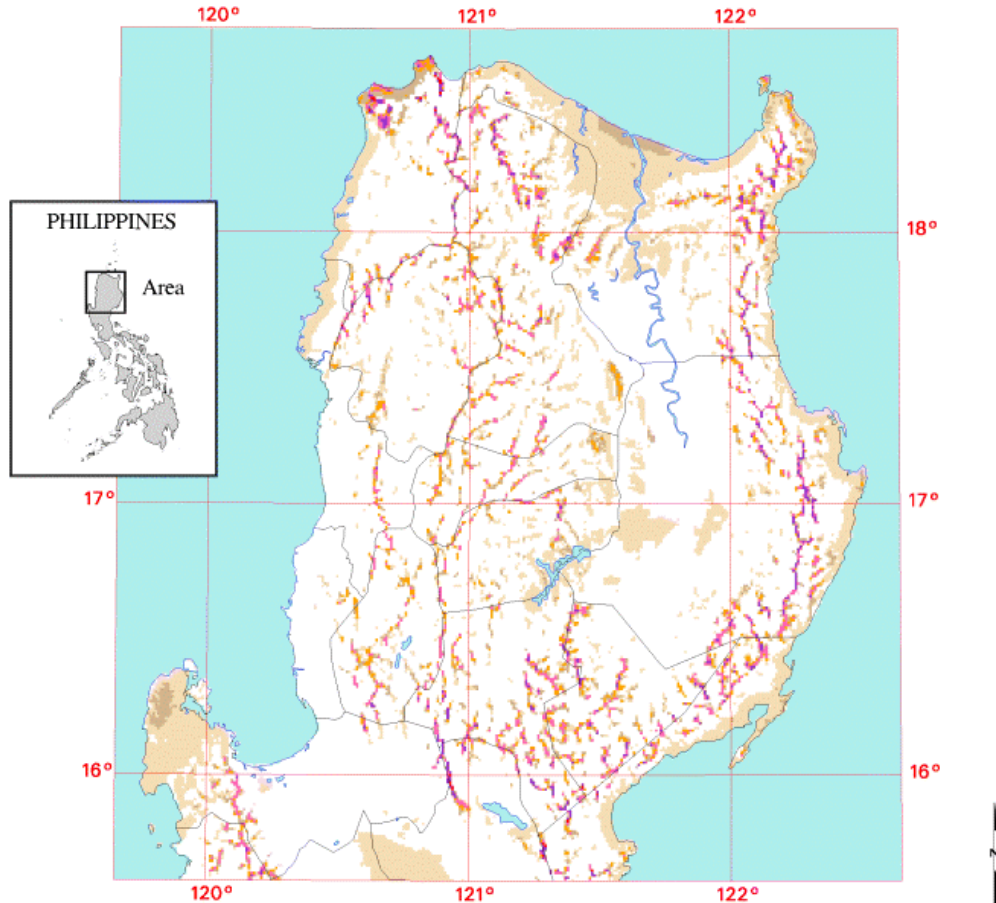
- 1 Turtle Mountain
- 2 Devil's Lake Sioux
- 3 Lake Traverse
- 4 Standing Rock
- 5 Fort Berthold

40 0 40 80 120 160 Kilometers  
25 0 25 50 75 100 Miles

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# Philippines - Northern Luzon Most Favorable Wind Resource Areas



## Wind Power Classification

Resource Potential		Wind Power Density at 30 m W/m <sup>2</sup>	Wind Speed <sup>a</sup> at 30 m m/s
Utility	Rural		
Marginal	Moderate	100 - 200	4.4 - 5.6
Moderate	Good	200 - 300	5.6 - 6.4
Good	Excellent	300 - 400	6.4 - 7.0
Excellent		400 - 600	7.0 - 8.0
		600 - 800	8.0 - 8.8
		800 - 1200	8.8 - 10.1

<sup>a</sup> Wind speeds are based on a Weibull k value of 2.0

The wind resource classification is specific for both utility scale and rural applications and applies to areas with low surface roughness.

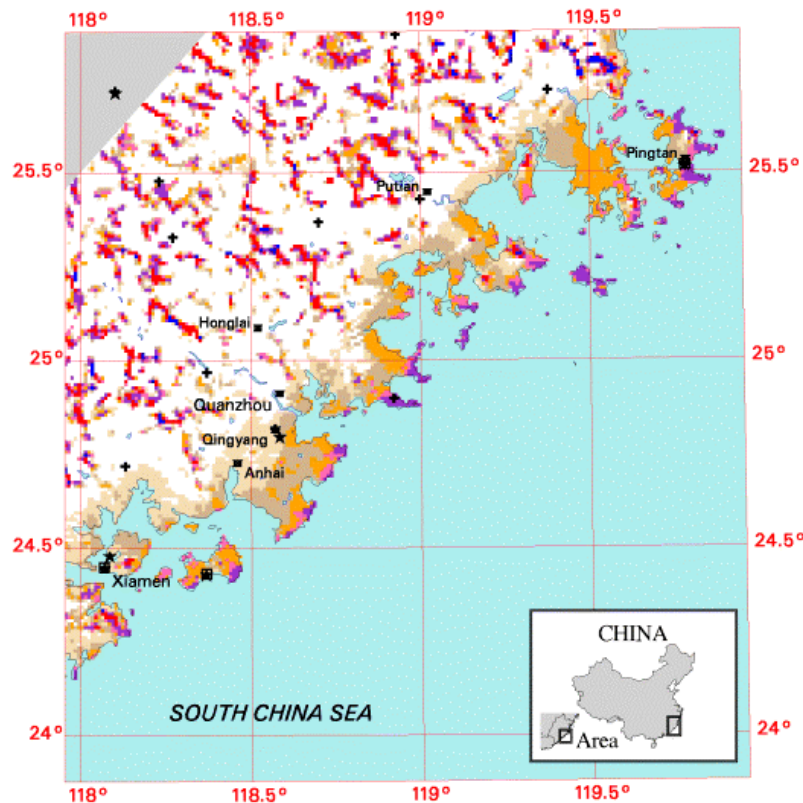
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NREL contacts:  
Dennis Elliott  
Marc Schwartz





# Southeast China - Central Coast of Fujian Map of Favorable Wind Resource Areas



## Wind Power Classification

Resource Potential	Wind Power Density at 30 m $W/m^2$	Wind Speed <sup>a</sup> at 30 m m/s
Fair	100 - 200	4.4 - 5.6
Moderate	200 - 300	5.6 - 6.4
Good	300 - 400	6.4 - 7.0
	400 - 500	7.0 - 7.5
Excellent	500 - 700	7.5 - 8.4
	700 - 1000	8.4 - 9.6
	> 1000	> 9.6

<sup>a</sup> Wind speeds are based on a Weibull k value of 2.0 estimated for many coastal areas of SE China.

- ★ GTS Surface Meteorological Station
- GTS Upper-Air Meteorological Station
- + Additional Surface Meteorological Station
- City

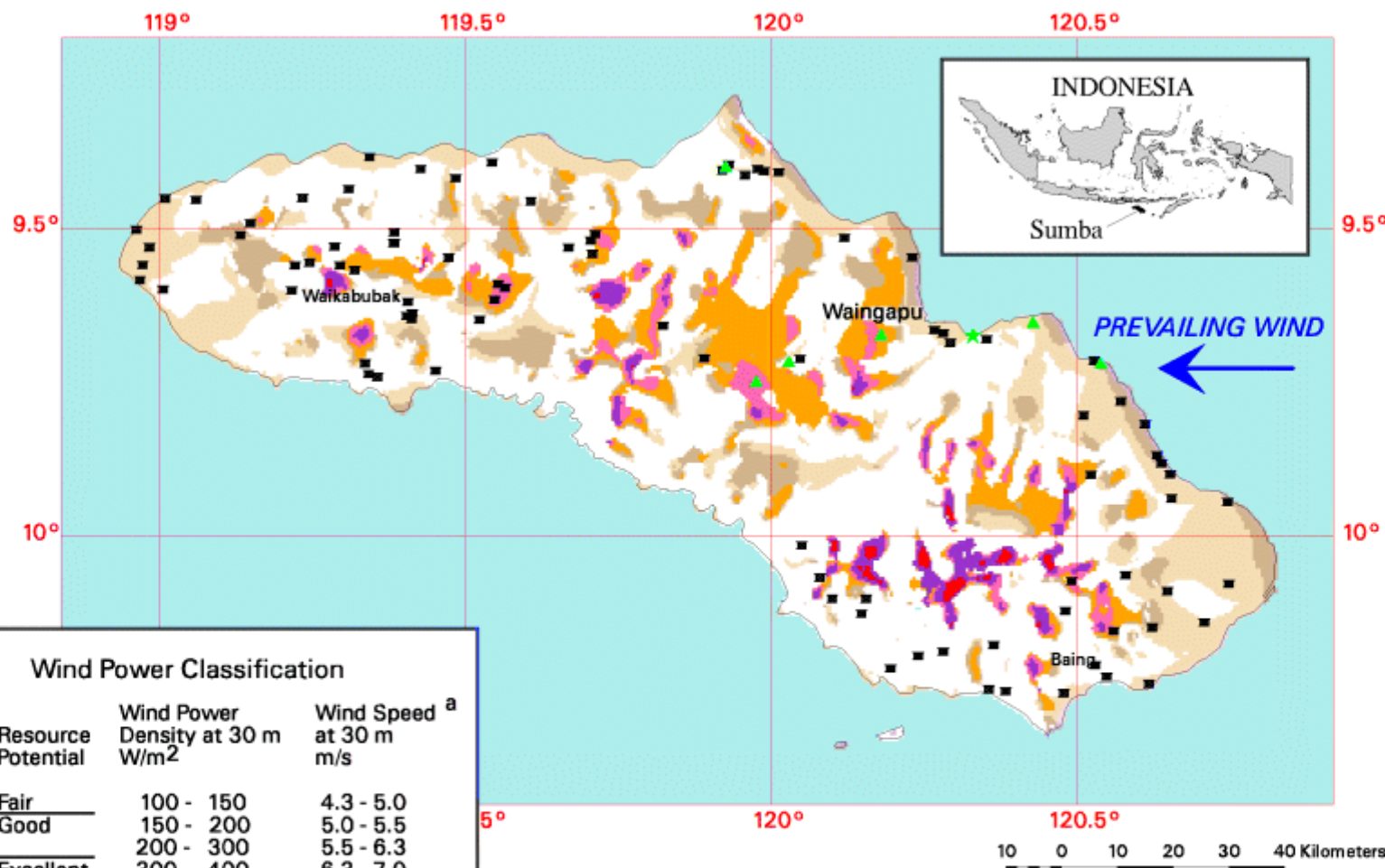
The wind resource classification is for utility scale applications and applies to areas with low surface roughness. The Global Telecommunications System (GTS) meteorological stations are part of NREL's global database. The data for the additional meteorological stations were provided by the State Power Company of China.

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Dennis Elliott (303) 384-6935  
Marc Schwartz (303) 384-6936



# Sumba, Indonesia - Favorable Wind Resource Areas

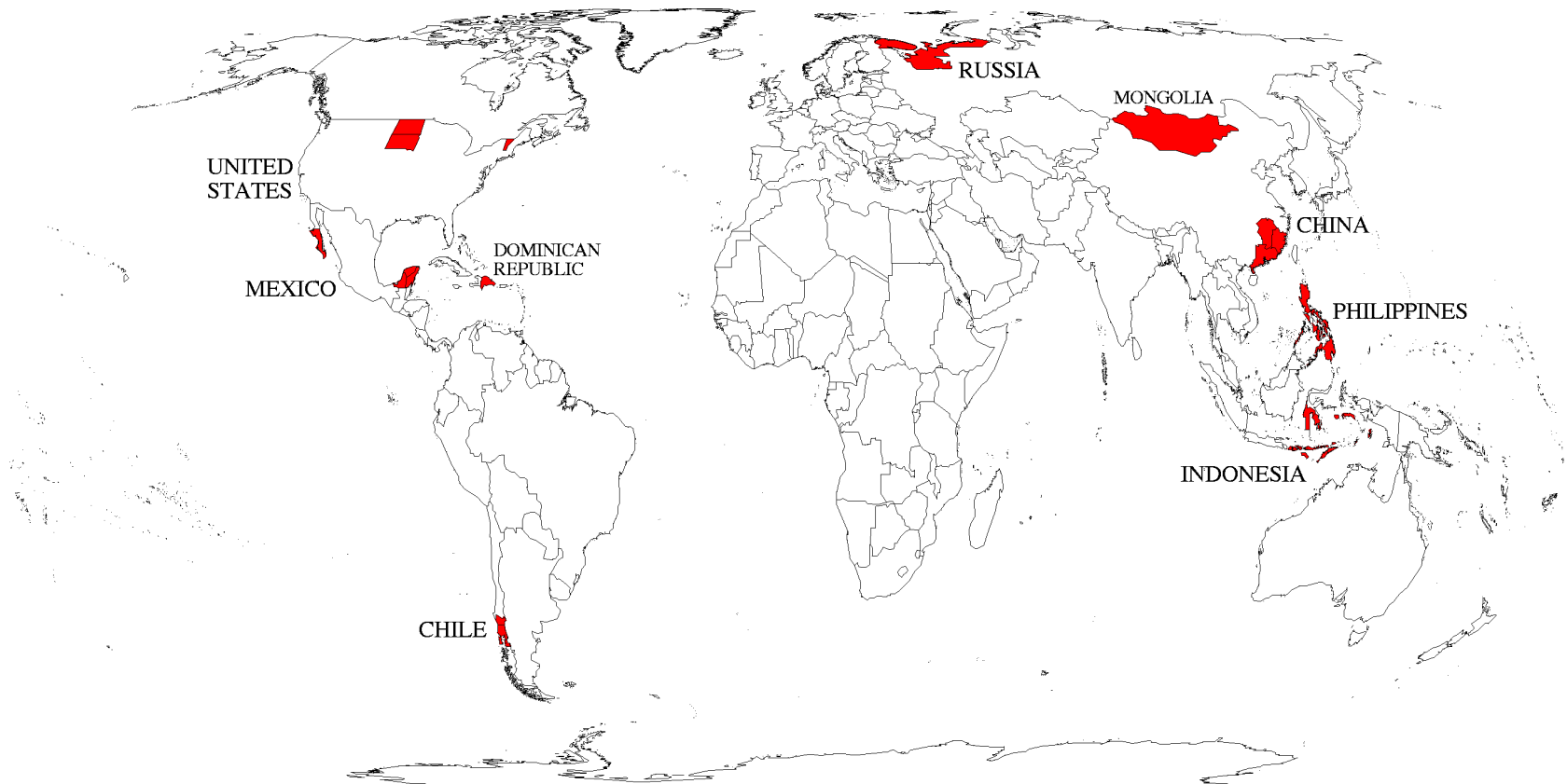


# *Applications of NREL's Wind Mapping System*

Used to produce high-resolution (1km<sup>2</sup>) regional or national wind resource maps

- United States - Dakotas, Vermont
- Mexico - Baja California Sur, Yucatan Peninsula
- Chile - Regions IX and X (Central Chile)
- Indonesia - Southeastern islands
- China - Southeastern areas
- Philippines - entire country
- Dominican Republic - entire country
- Mongolia - entire country

# NREL Wind Resource Mapping Projects Since 1996



The project areas are shown to the provincial or state level and may not represent the true extent of the actual wind maps. All of the maps including the high resolution (1 km) wind resource maps are developed with NREL's GIS-based mapping system.

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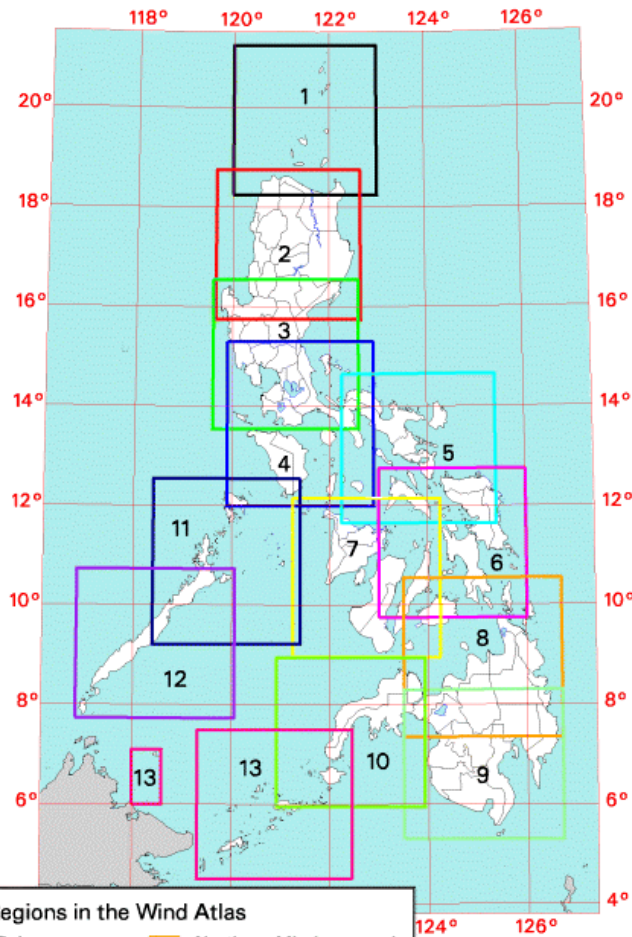
*Product Examples*  
*Developing Country*  
*Philippines Wind Atlas*

# ***Wind Energy Resource Atlas of the Philippines Contents***

- EXECUTIVE SUMMARY
- INTRODUCTION
- GEOGRAPHY AND CLIMATE OF THE PHILIPPINES
- WIND RESOURCE DATA IN THE PHILIPPINES
- WIND RESOURCE ASSESSMENT AND MAPPING METHODOLOGY
- WIND RESOURCE CHARACTERISTICS OF THE PHILIPPINES
- WIND MAPPING AND IDENTIFICATION OF RESOURCE AREAS
- WIND ELECTRIC POTENTIAL OF THE PHILIPPINES
- REFERENCES
- APPENDICES

# Philippines

## Key to the Regions in the Wind Atlas



### Regions in the Wind Atlas

- |  |  |
|--|--|
| <b>1</b> Batanes and Babuyan                             | <b>8</b> Northern Mindanao and Bohol   |
| <b>2</b> Northern Luzon                                  | <b>9</b> Southern Mindanao             |
| <b>3</b> Central Luzon                                   | <b>10</b> Western Mindanao and Basilan |
| <b>4</b> Southern Luzon, Mindoro, Romblon and Marinduque | <b>11</b> Northern Palawan             |
| <b>5</b> Southeastern Luzon, Catanduanes and Masbate     | <b>12</b> Southern Palawan             |
| <b>6</b> Samar and Leyte                                 | <b>13</b> Basilan, Sulu and Tawi-Tawi  |
| <b>7</b> Panay, Negros, Cebu and Siquijor                |  |

100 0 100 200 300 400 Kilometers

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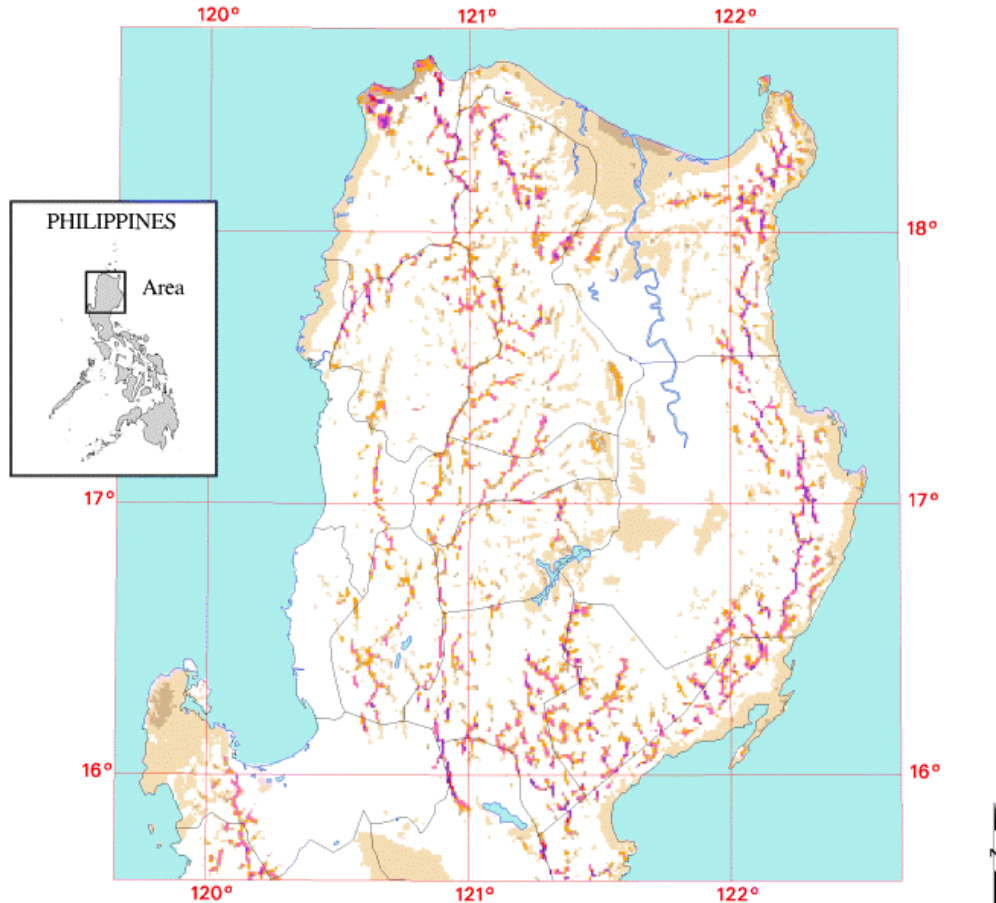
NREL contacts:  
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Marc Schwartz



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# Philippines - Northern Luzon Most Favorable Wind Resource Areas



## Wind Power Classification

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<sup>a</sup> Wind speeds are based on a Weibull k value of 2.0

The wind resource classification is specific for both utility scale and rural applications and applies to areas with low surface roughness.

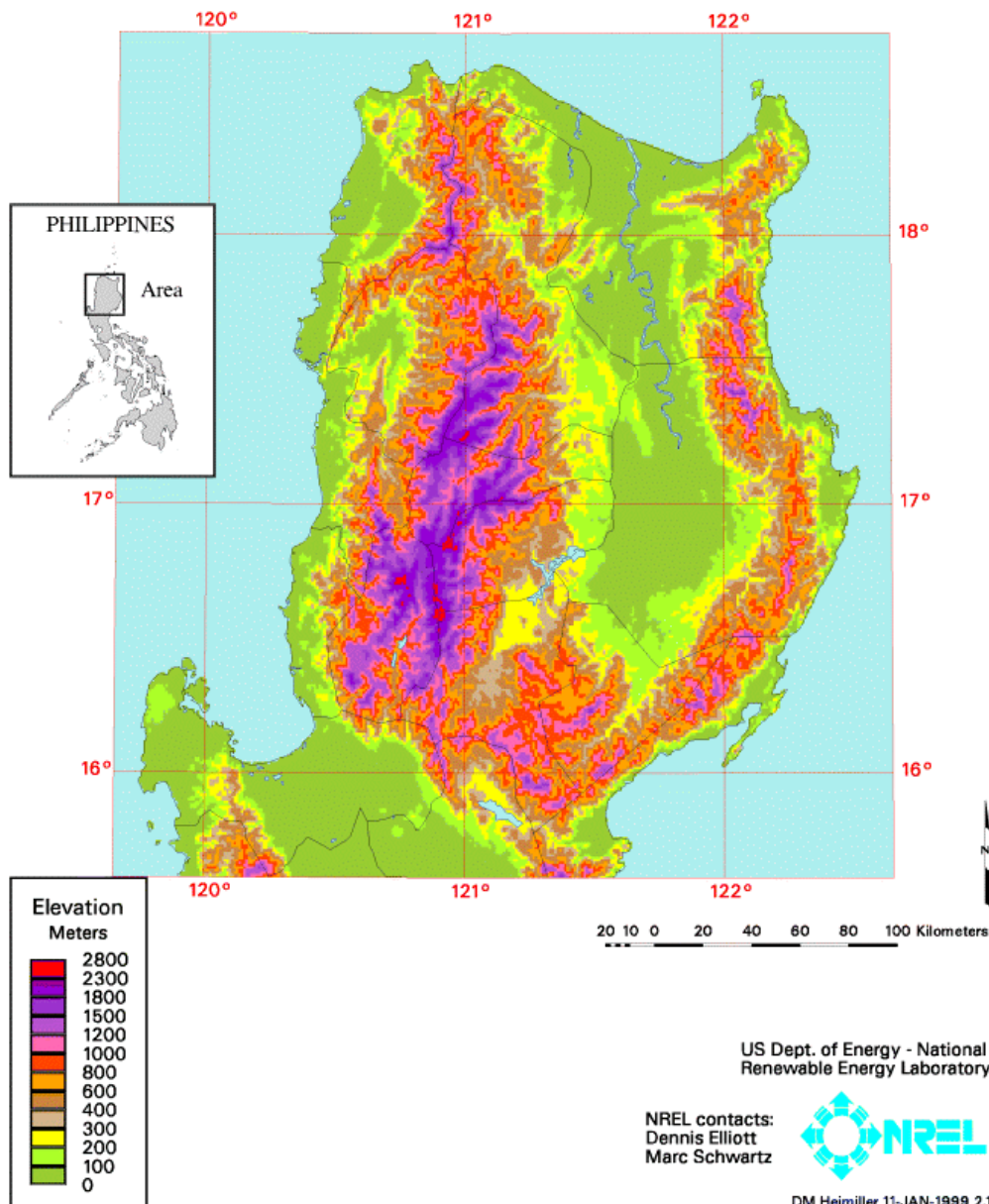
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# Philippines - Northern Luzon Elevation Map



PHILIPPINES

Area



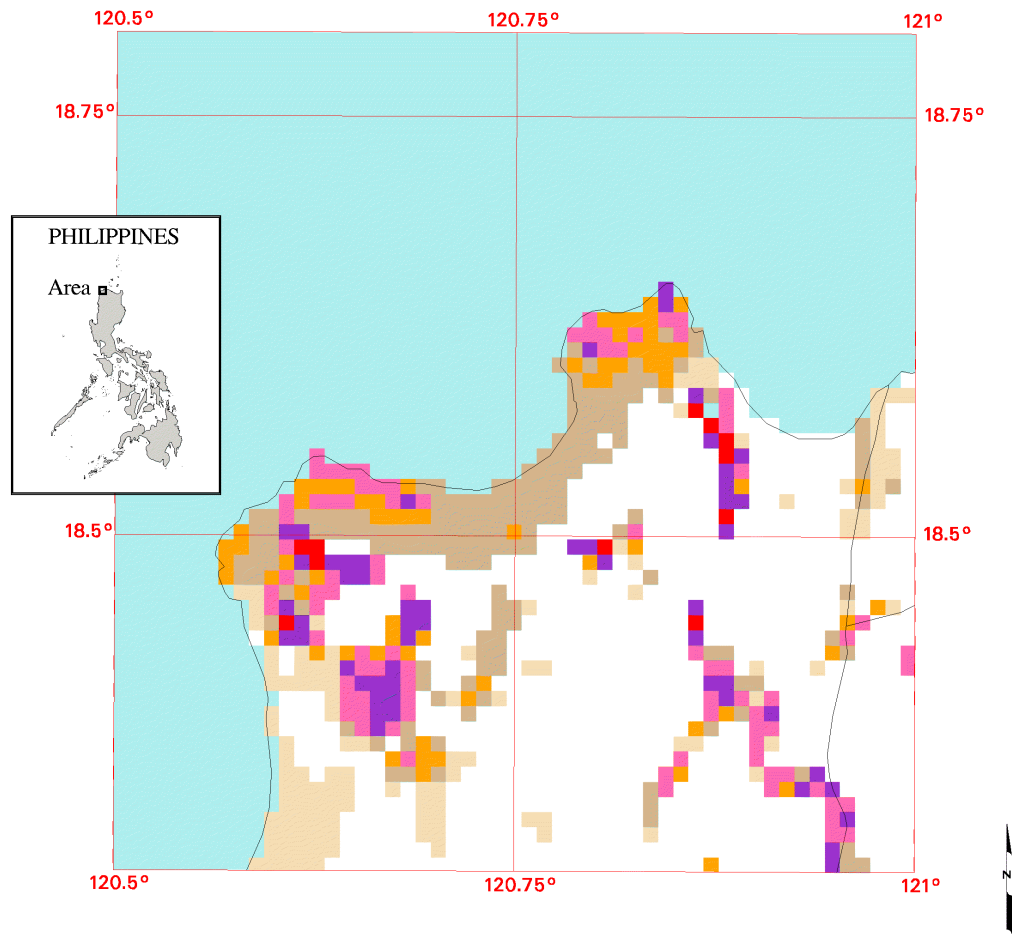
20 10 0 20 40 60 80 100 Kilometers

### Legend

- + GTS Surface Meteorological Station with Wind Data
- GTS Upper-Air Meteorological Station
- × NPC Wind Measurement Site
- City or Provincial Capital



# Philippines - Northwest Tip of Luzon Most Favorable Wind Resource Areas



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## **PHILIPPINES - WIND ELECTRIC POTENTIAL**

Good-to-Excellent Wind Resource at 30 m (Utility Scale)

<b>Wind Resource Utility Scale</b>	<b>Wind Power W/m<sup>2</sup></b>	<b>Wind Speed m/s</b>	<b>Total Area km<sup>2</sup></b>	<b>Total Capacity Installed MW</b>	<b>Total Power GWh/yr</b>
<b>Good</b>	<b>300-400</b>	<b>6.4-7.0</b>	<b>5,541</b>	<b>38,400</b>	<b>85,400</b>
<b>Excellent</b>	<b>400-500</b>	<b>7.0-8.0</b>	<b>2,841</b>	<b>19,700</b>	<b>52,200</b>
<b>Excellent</b>	<b>500-700</b>	<b>8.0-8.8</b>	<b>2,258</b>	<b>15,600</b>	<b>47,900</b>
<b>Excellent</b>	<b>700-1250</b>	<b>8.8-10.1</b>	<b>415</b>	<b>2,900</b>	<b>9,700</b>
<b>Total</b>			<b>11,055</b>	<b>76,600</b>	<b>195,200</b>

### **Assumptions**

**Turbine Size – 500 kW**

**Hub Height – 40m**

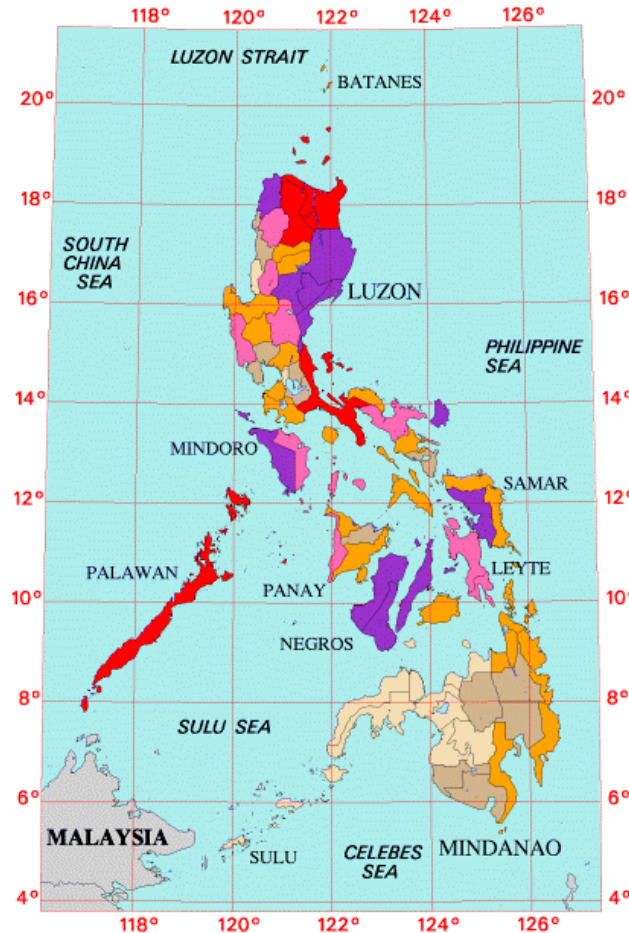
**Rotor Diameter – 38m**

**Turbine Spacing – 10D by 5D**

**Capacity/km<sup>2</sup> – 6.9 MW**

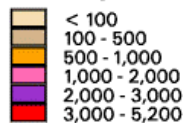
# Philippines - Wind Electric Potential

## Good-to-Excellent Wind Resource (Utility Scale Classification)



Philippines Total - 76,600 MW

### Wind Electric Potential Megawatts



The following assumptions were used in calculating the total potential wind electric capacity installed:

Minimum wind power - 300 W/m<sup>2</sup>  
Turbine size - 500 kW  
Hub height - 40 m  
Rotor diameter - 38 m  
5D Side-to-side spacing - 190 m  
10D Front-to-back spacing - 380 m  
Swept area - 1134 m<sup>2</sup>  
Turbines/km<sup>2</sup> - 13.9  
Capacity/km<sup>2</sup> - 6.9 MW

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Renewable Energy Laboratory

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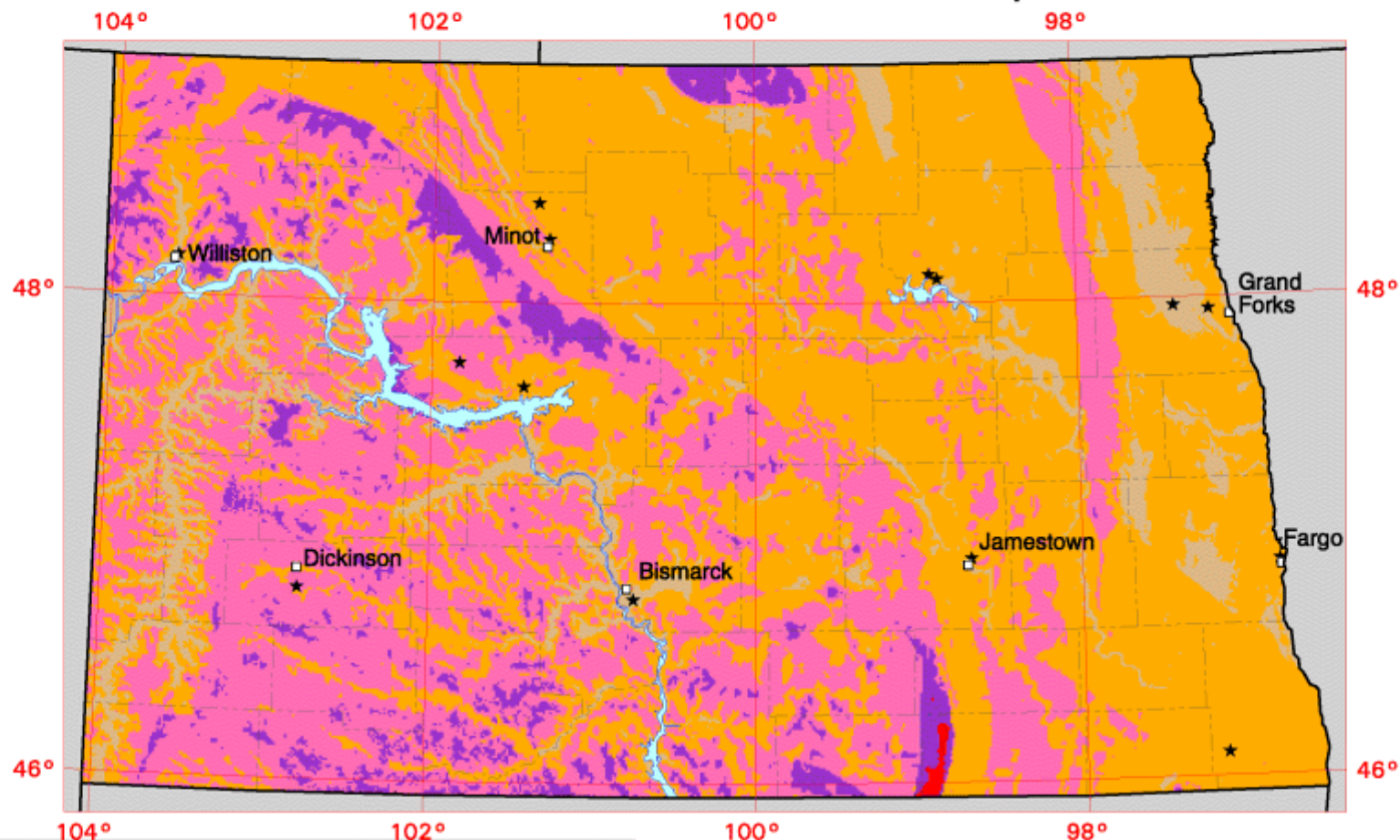


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*Product Examples*  
*Wind Powering America*  
*North Dakota*



# North Dakota - Wind Resource Map



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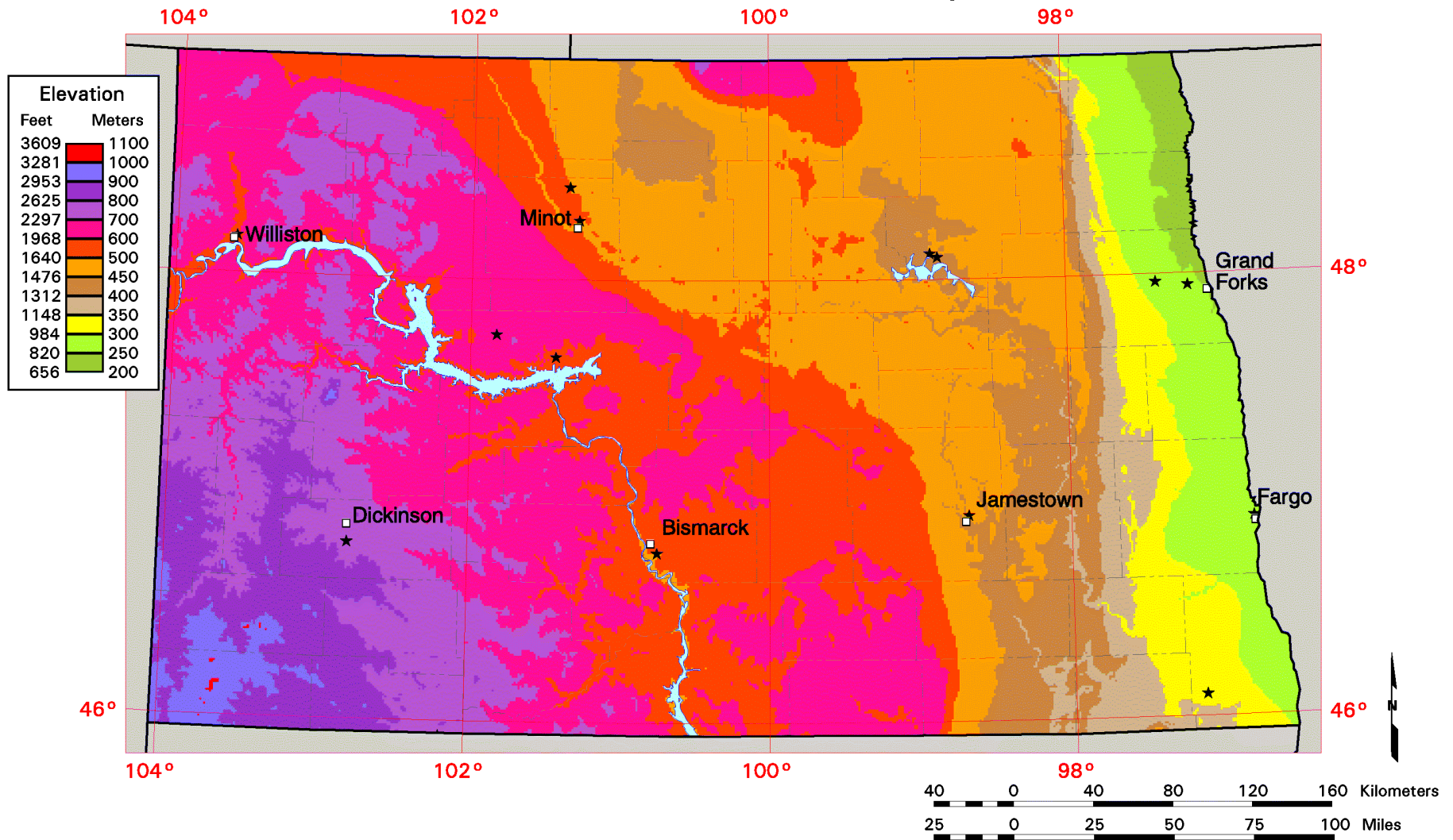
- ★ Meteorological Station with Wind Data
- City or Town

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# North Dakota - Elevation Map



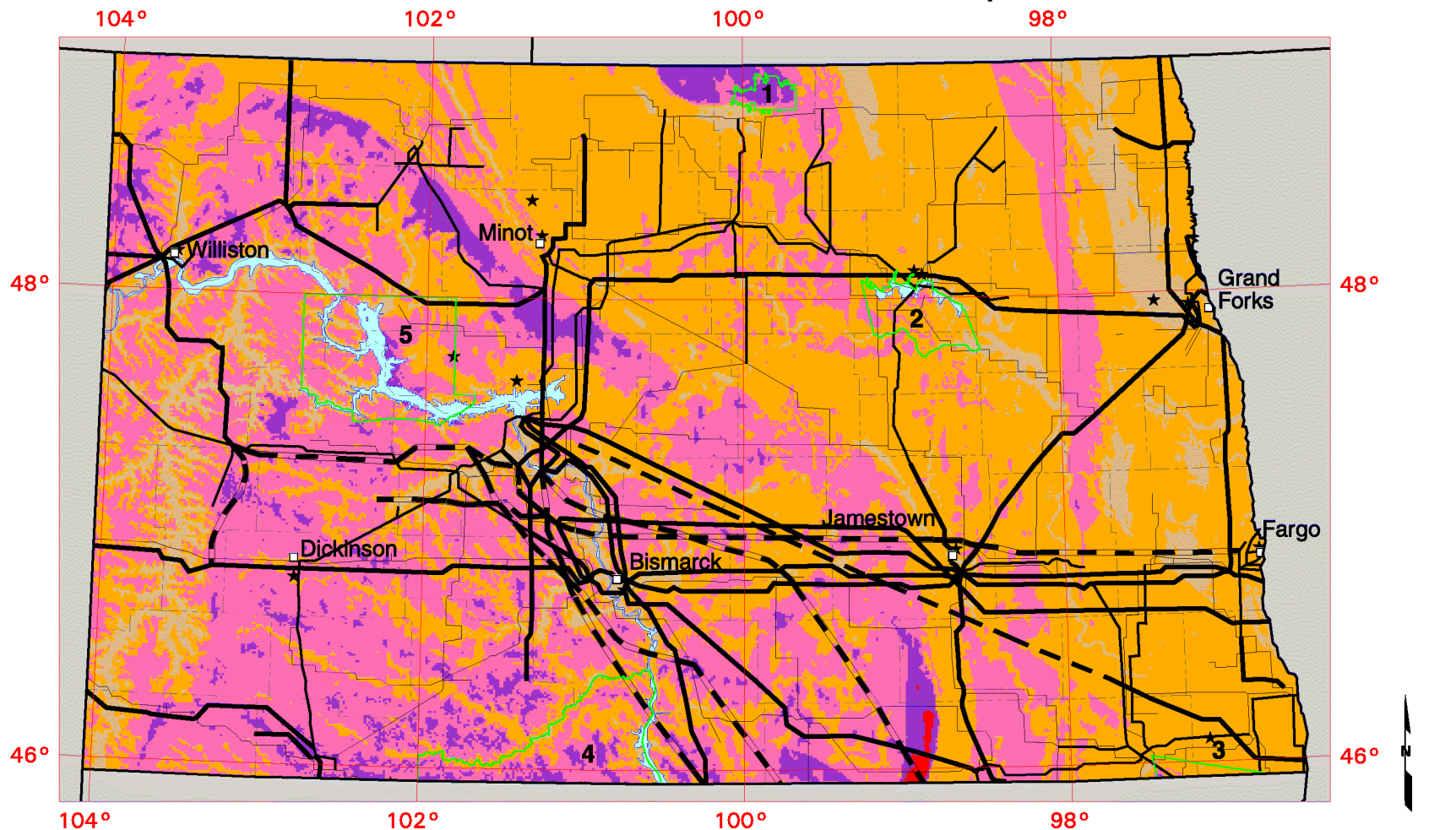
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# North Dakota - Wind Resource Map



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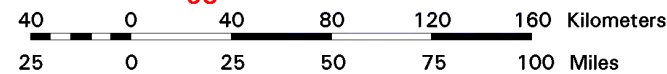
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## Transmission Line Voltage

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- 345 Kilovolts
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## Indian Reservations

- 1 Turtle Mountain
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# *NREL's GIS-based Wind Mapping System*

## *NREL's Wind Mapping System*

- Computerized mapping system started in 1995
- Uses Geographical Information System (GIS) software (ArcInfo<sup>®</sup> and ArcView<sup>®</sup>)
- Designed for regional wind mapping (not micro-siting)
- Empirical and analytical approach
- Does not depend on high quality surface wind observations
- Model inputs - formatted meteorological data and digital terrain data

# *Logic of Mapping System*

## ■ Model Design

- ARC/INFO® GIS-based
  - ◆ 31 custom programs
  - ◆ Over 16,000 lines of code
- Modules for physiographic settings
  - ◆ Inland
  - ◆ Coastal and Islands
  - ◆ Lake shores
- Modules for terrain settings
  - ◆ Complex - mountainous terrain
  - ◆ Flat - includes sloping terrain and minor relief
  - ◆ Mixed - a combination of complex and flat terrain
- Appropriate modules are applied
- Model domain larger than mapping domain

# *Logic of Mapping System*

- Inputs for computerized wind mapping
  - Meteorological Data
    - ◆ Vertical profile of wind power
    - ◆ Near surface wind power for coastal/ocean areas
    - ◆ Wind power rose (percent of power by direction)
  - Digital Geographic Data
    - ◆ Terrain - 1km<sup>2</sup> elevation data
    - ◆ Coastline and hydrography
  - Geographic zones for meteorological data

# *Data Collection for Model Inputs*

- NREL's global meteorological data set
  - surface station data
  - upper-air data
  - ocean data (satellite, ship)
- Host-country meteorological service wind summaries and reports
- Other wind measurement data available from host country
- NREL's global terrain and geographic data

## Major Global Data Sets used by NREL for Wind Resource Assessment

<b><u>Data Set</u></b>	<b><u>Type of Information</u></b>	<b><u>Source</u></b>	<b><u>Period of Record</u></b>
Surface Station Data	Surface observations at 20000 stations	NOAA/NCDC	1973-1998
Upper Air Station Data	Rawinsonde and pibal observations at 1800 stations	NCAR	1973-1998
Satellite-derived Ocean Wind Data	10-m ocean wind speeds gridded to 0.25 deg	NASA/JPL	1988-1998
Marine Climatic Atlas of the World	Gridded (1.0 deg) statistics of historical ship wind observations	NOAA/NCDC	1854-1969
Reanalysis Upper Air Data	Model-derived gridded (~200km) upper air data	NCAR	1958-1997
Global Upper Air Climatic Atlas	Model-derived gridded (2.5 deg) upper air statistics	NOAA/NCDC	1980-1991
Digital Geographic Data	Political, hydrography, etc.	ESRI	
Digital Terrain Data	Elevation – 1 km resolution	USGS/EROS	

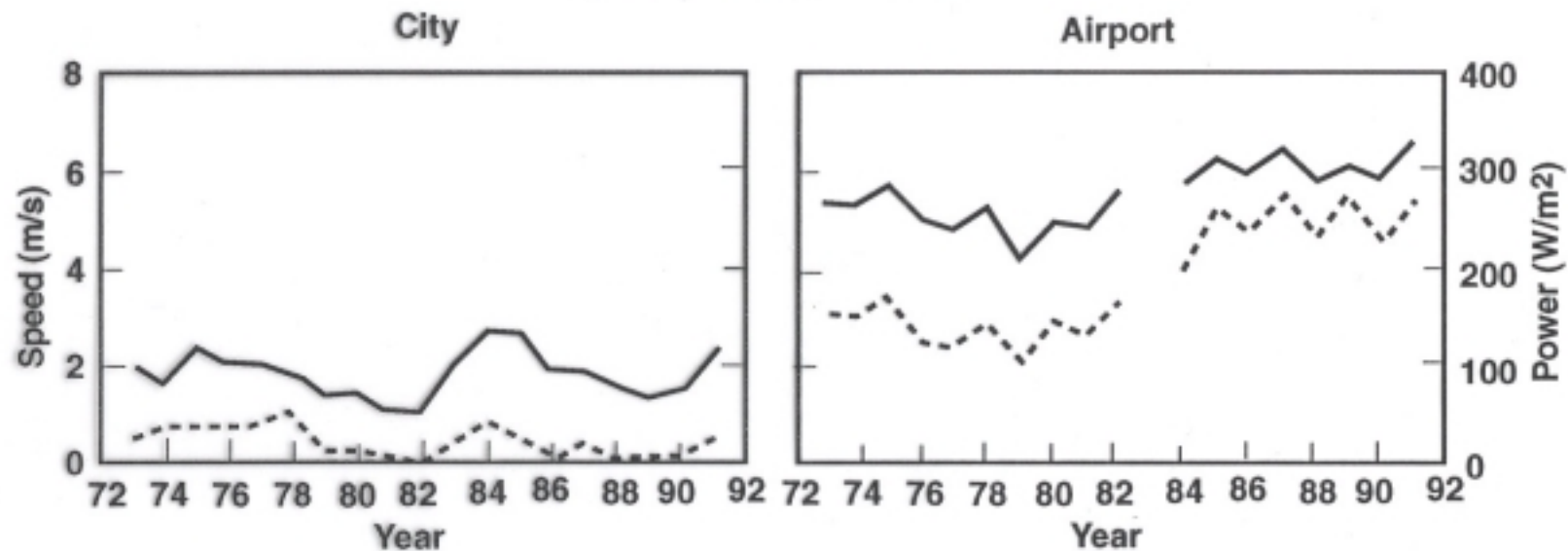
# *NREL's Quality Assessment of Meteorological Data*



# Chetumal, Mexico Yucatan Peninsula - East Coast

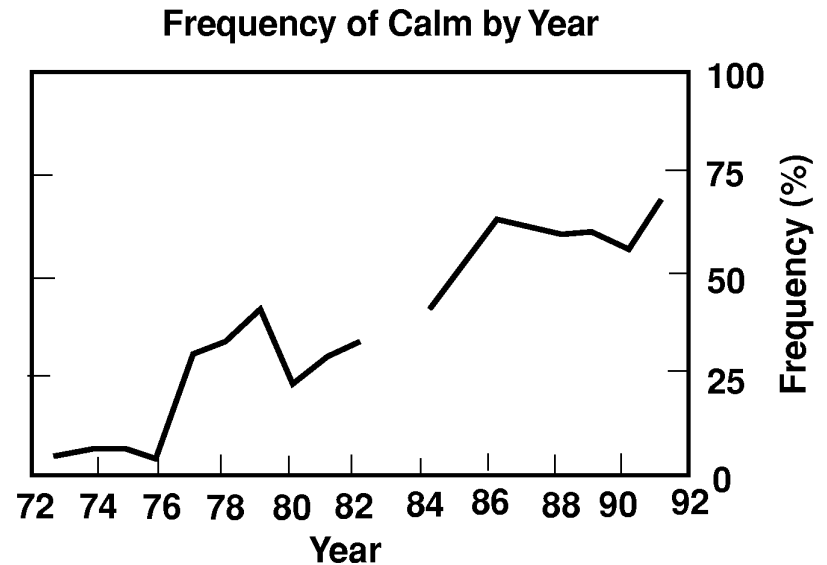
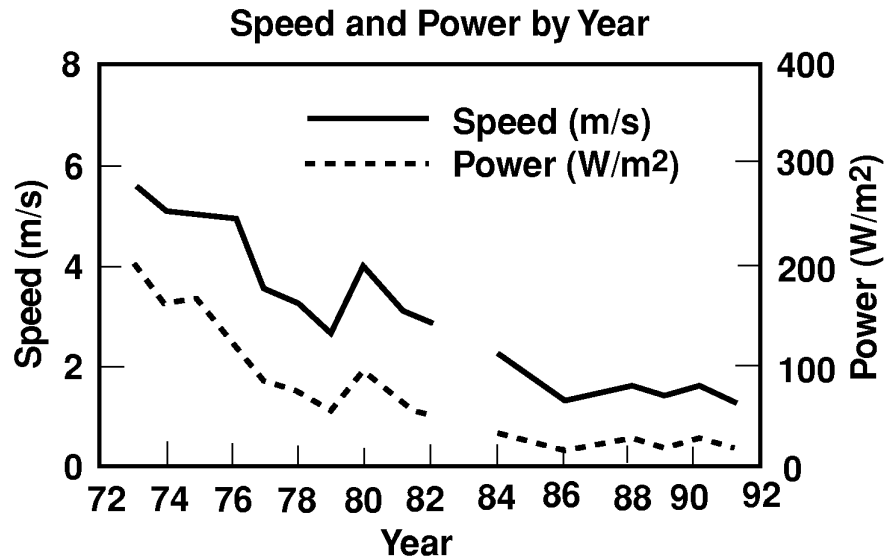
— Speed (m/s)  
- - - Power (W/m<sup>2</sup>)

Speed and Power by Year



	Period	Speed (m/s)	Power (W/m <sup>2</sup> )
City	1973-91	1.9	22
Airport	1984-91	6.1	245

# Mexicali Airport, Mexico Baja California

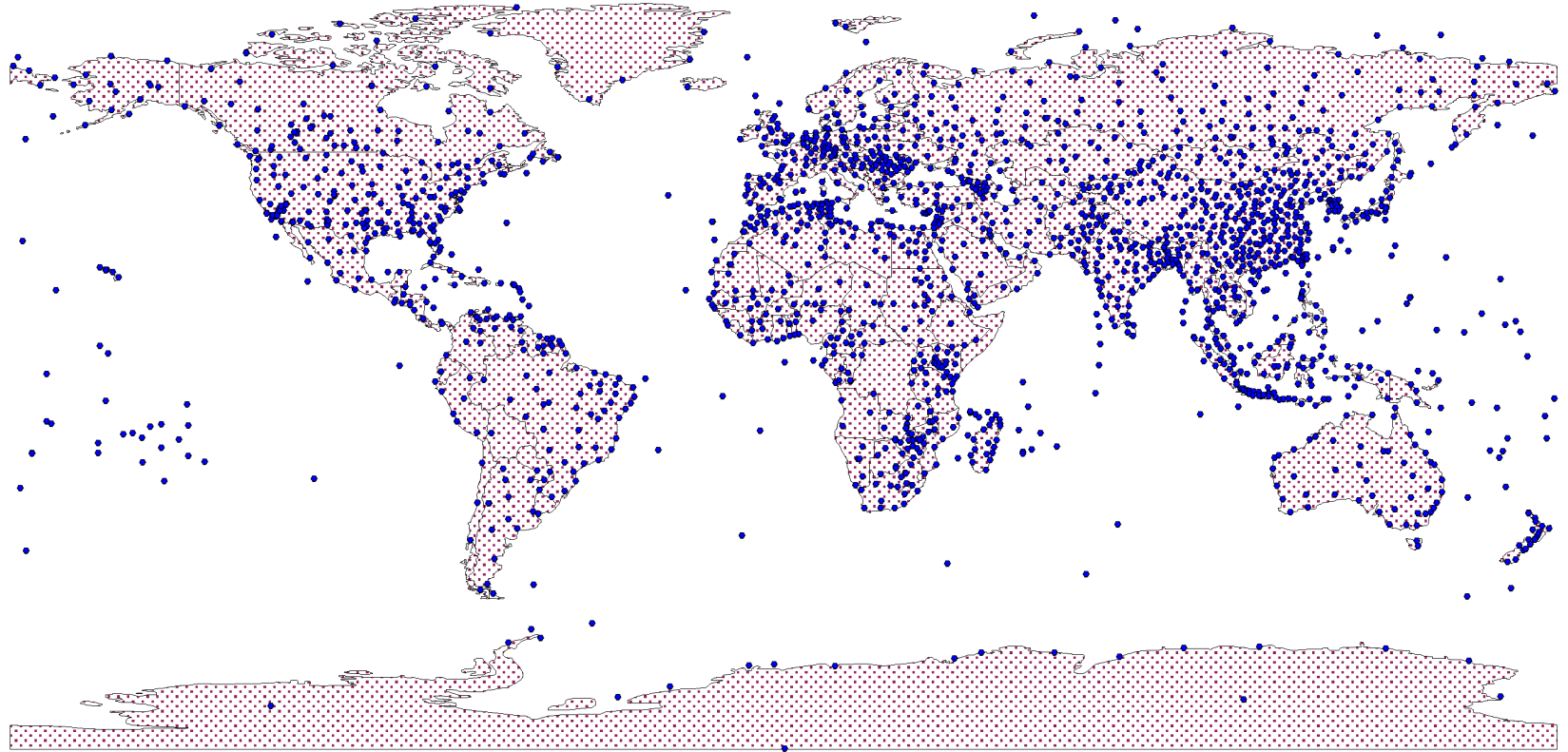


Period	Wind Speed (m/s)	Power (W/m <sup>2</sup> )	Calm (%)
1973-75	5.2	170	7
1986-91	1.5	20	62

## Comparison of Wind Power Densities for Selected Areas in Mexico

		Wind Power Density (W/m <sup>2</sup> )	
		OLADE Atlas (1983)	NREL Analysis (1995)
Yucatan Peninsula	Merida	22	165
	Campeche	23	120
	Chetumal	28	205
Northern Gulf Plain	Tampico	8	205
	Ciudad Victoria	32	170
	Matamoros	32	165
Central Highlands	Durango	8	140
	San Luis Potosi	35	155
	Zacatecas	94	270
Northwest	Chihuahua	27	120
	Hermosillo	3	80
	La Paz	10	85

# Worldwide Weather Balloon Launch Sites



## *Logic of Mapping System (cont.)*

- Meteorological data, digital geographic data, and GIS software combined in wind power calculation modules
- Uses “top down” method to adjust free-air winds for estimating base wind power density values
- Base wind power density values are adjusted by terrain and stability factors in model

# *Output of Mapping System*

- Final products
  - wind power density maps (1 km<sup>2</sup> resolution)
  - topographic maps (1 km<sup>2</sup> resolution)
  - political and other types of maps
- Estimates of wind power density displayed for most favorable areas, considering:
  - level of wind resource
  - exposure to prevailing winds
  - terrain slope

## *Conclusions*

- Cursory methods in many previous surveys underestimate wind potential
- Comprehensive approach and various types of data are used to develop reliable assessments
- Many areas of good wind potential have been identified that were previously estimated to have inadequate potential
- Advanced GIS modeling of wind resource results in more sophisticated, detailed and consistent analysis
- Reliable wind resource maps identify optimum locations for measurement programs and facilitate project decisions

# *Appendices*



# *Wind Resource Assessment and Mapping at NREL*

## **NREL's Wind Resource Assessment Group**

Dennis Elliott (team leader)

Marc Schwartz

George Scott

Steve Haymes

Donna Heimiller

Ray George

# *Basic Principles of Wind Resource Estimation*

## WIND POWER RELATIONSHIPS

$$P = \frac{1}{2} \rho A V^3$$

↓
↓
↓
↓

AVAILABLE POWER      AIR DENSITY      SWEEP AREA      WIND VELOCITY CUBED

EXAMPLE: SAME TURBINE, SEA LEVEL,  
DIFFERENT SITE

$$P = KV^3$$

$$\text{WIND VELOCITY} = v \quad P_1 = Kv^3$$

$$\text{WIND VELOCITY} = 2v \quad P_2 = 8Kv^3$$

$$P_2 = 8P_1$$

EXAMPLE: DIFFERENT TURBINE, SEA LEVEL,  
SAME SITE

$$P = Cd^2$$

$$\text{ROTOR DIAMETER} = d \quad P_1 = Cd^2$$

$$\text{ROTOR DIAMETER} = 2d \quad P_2 = 4Cd^2$$

$$P_2 = 4P_1$$

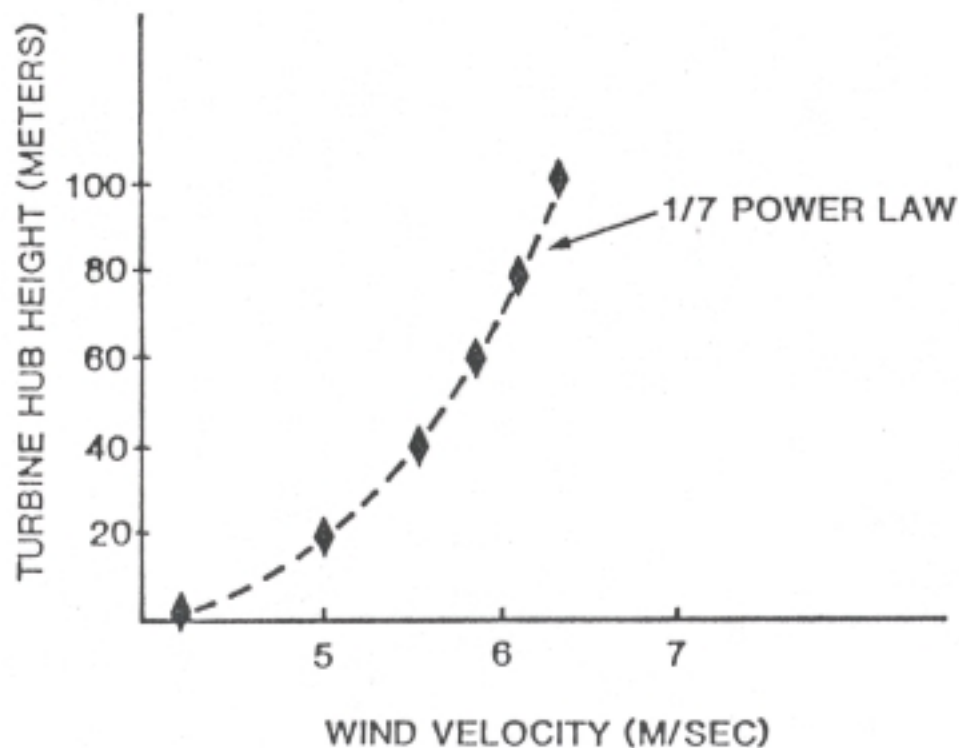
## Comparison of Annual Average Wind Power at Four Sites with Identical Annual Average Wind Speeds at 10 m

Site	Annual Average Wind Speed, m/s (mph)	Annual Average Wind Power Density, W/m <sup>2</sup>	Wind Power Power Class
Constant Wind Speed (hypothetical)	6.3 (14)	150	2-3
Culebra, Puerto Rico	6.3 (14)	220	4
Tiana Beach, New York	6.3 (14)	285	5
San Geronio, California	6.3 (14)	365	6

## WIND VELOCITY VERSUS ALTITUDE

$$\frac{V}{V_0} = \left( \frac{H}{H_0} \right)^n$$

WHERE:  $V_0$  = REFERENCE WIND VELOCITY  
 $H_0$  = REFERENCE HEIGHT  
 $n$  = DEPENDENT EXPONENT



## *History of Wind Mapping in DOE's Wind Program*

### **Late 1970s - 1980s**

- Maps produced by subjective analysis and interpolation
- Reliable surface data key to quality of results
- Examples: US atlas, global map

### **Early 1990s**

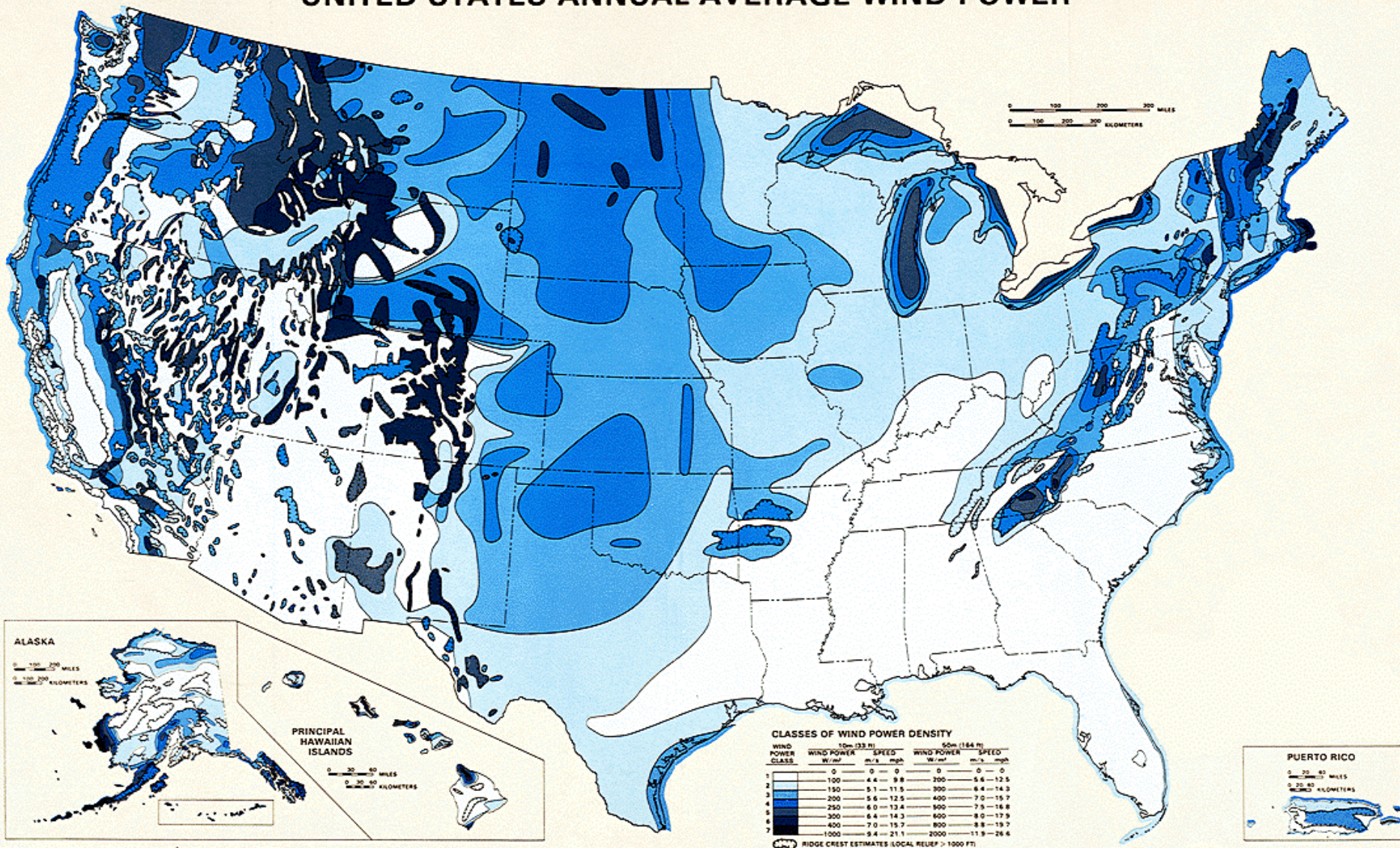
- New global meteorological data sets offer potential for improved wind assessments (e.g., Mexico, Indonesia)
- New digital geographic data sets facilitate GIS-based mapping (e.g., Digital Chart of the World)

### **Late 1990s**

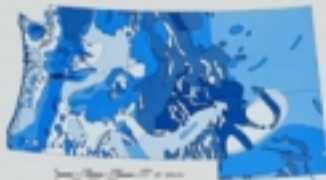
- Development of NREL's GIS-based wind mapping system
- Improvements in data analysis and assessment techniques
- Wind mapping applications in diverse regions of the world
- Validation of mapping results



# UNITED STATES ANNUAL AVERAGE WIND POWER

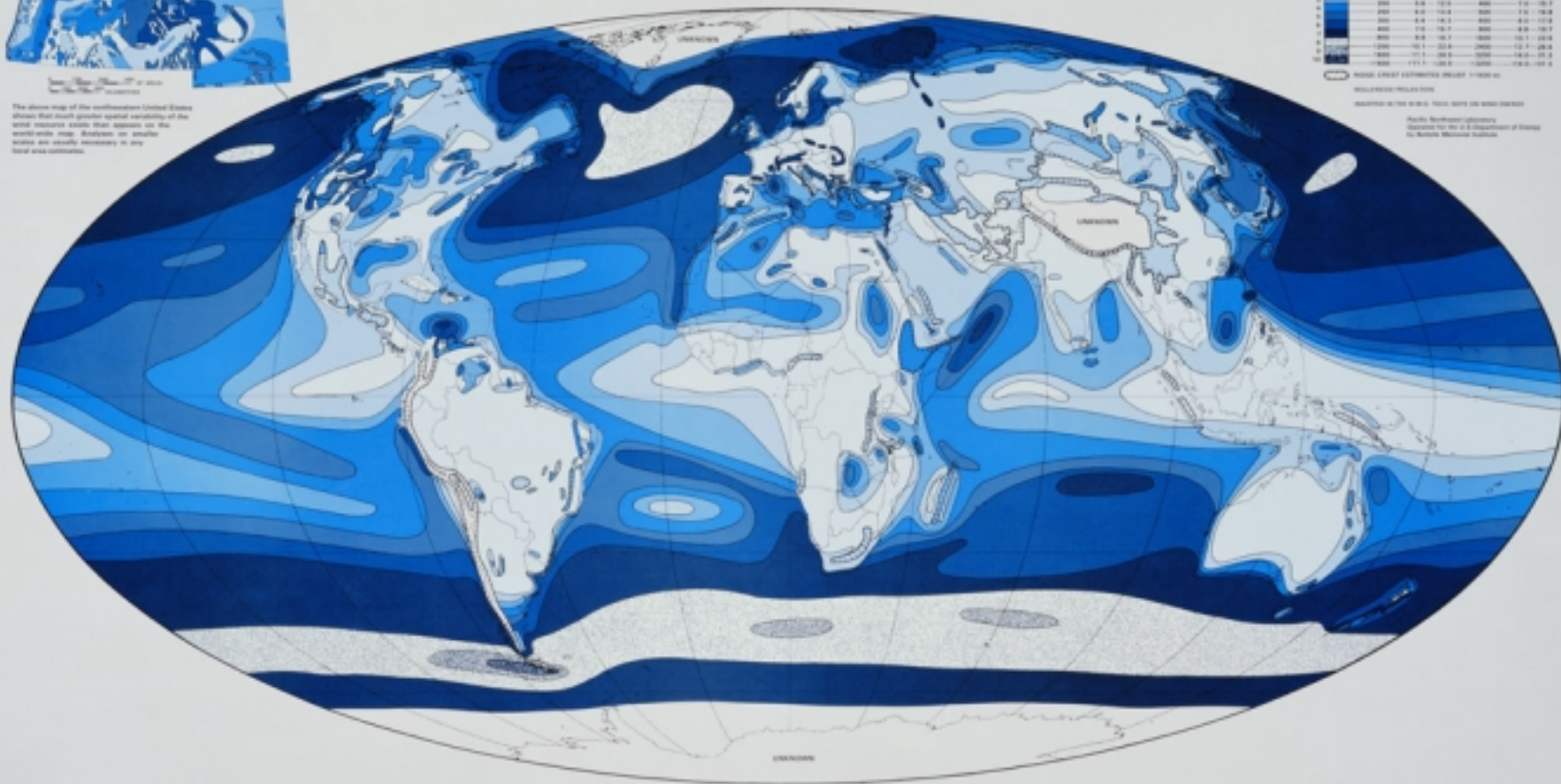






The above map of the northwestern United States shows that much greater spatial variability of the wind resource exists than appears on the world-wide map. However, no similar studies are currently necessary in any local area estimates.

## WORLD-WIDE WIND ENERGY RESOURCE DISTRIBUTION ESTIMATES



### CLASSES OF WIND ENERGY FLUX (WEF)

WIND ENERGY CLASS	WEF (10 <sup>3</sup> W/m <sup>2</sup> )	WEF (10 <sup>3</sup> W/m <sup>2</sup> )	WEF (10 <sup>3</sup> W/m <sup>2</sup> )	WEF (10 <sup>3</sup> W/m <sup>2</sup> )
1	0	0	0	0
2	0.5	0.5	0.5	0.5
3	1.0	1.0	1.0	1.0
4	1.5	1.5	1.5	1.5
5	2.0	2.0	2.0	2.0
6	2.5	2.5	2.5	2.5
7	3.0	3.0	3.0	3.0
8	3.5	3.5	3.5	3.5
9	4.0	4.0	4.0	4.0
10	4.5	4.5	4.5	4.5
11	5.0	5.0	5.0	5.0
12	5.5	5.5	5.5	5.5
13	6.0	6.0	6.0	6.0
14	6.5	6.5	6.5	6.5
15	7.0	7.0	7.0	7.0
16	7.5	7.5	7.5	7.5
17	8.0	8.0	8.0	8.0
18	8.5	8.5	8.5	8.5
19	9.0	9.0	9.0	9.0
20	9.5	9.5	9.5	9.5
21	10.0	10.0	10.0	10.0
22	10.5	10.5	10.5	10.5
23	11.0	11.0	11.0	11.0
24	11.5	11.5	11.5	11.5
25	12.0	12.0	12.0	12.0

WIND ENERGY FLUX (WEF)

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### MAP DESCRIPTION

This map is a preliminary estimate of the annual mean wind energy available at typical wind exposure locations throughout the world. The average energy in the wind flowing in the layer near the ground is represented as a wind energy class. The greater the average wind energy, the higher the wind energy class, and the darker the shade of blue on the map. The colors corresponding to classes of wind energy are defined in the table at the upper right.

The wind energy class is defined in relation to the mean wind energy flux (WEF) at 10 m above ground level. The WEF is the

rate of flow of wind energy through a unit vertical area normal to the wind direction. At 10 m, the WEF estimate represents large areas that are relatively free of obstructions. Local terrain features can cause the mean wind energy to vary considerably over short distances, especially of coastal, hilly and mountainous areas. There will be local areas of higher or lower wind energy than can be shown on a world-wide map. This is demonstrated by the smaller scale map at the upper left.

### BACKGROUND INFORMATION

The relationship between the mean WEF and the mean wind speed is the table at the upper right assumes a Rayleigh distribution (Weibull with k = 2) for the wind speed frequency distribution. A 1.7 power law for mean wind speed and a 1.7 power law for mean WEF relate the WEF to estimates in the 10 m reference.

Because the wind energy estimates generally apply to typical well-exposed locations, the fraction of the land area lying within the wind energy class depends on the physical character

of the land surface form in the region. For example, on a flat open plain close to 100% of the area will have a similar wind energy class, while in hilly and mountainous areas the wind energy class will only apply to a small proportion of the area that is well exposed. On the map, areas where mountainous terrain generally exceeds 1000 m are shown using fine white tick marks. Within these areas wind resource estimates are for exposed ridge crests.

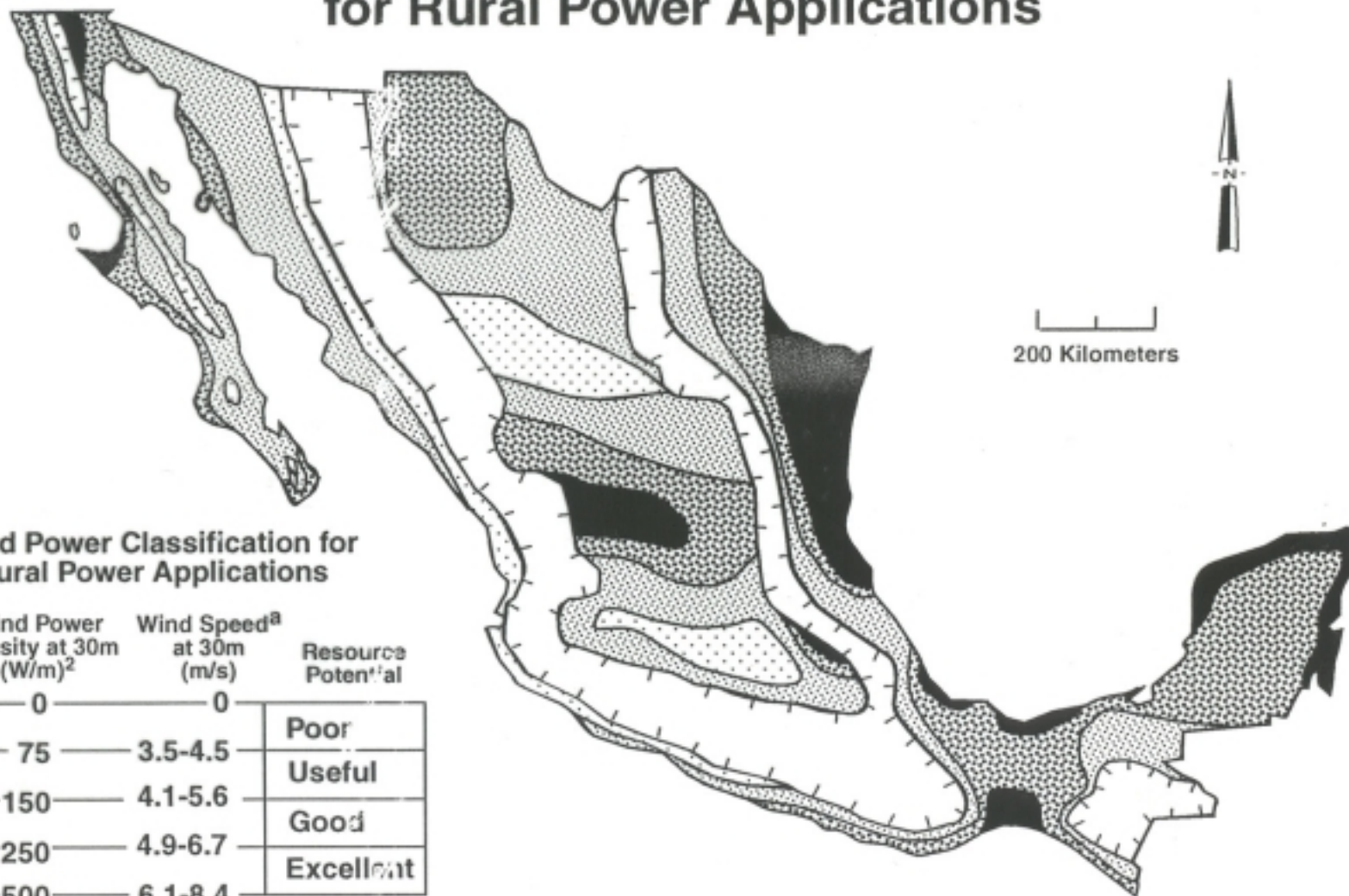
The mean wind energy may vary considerably with time of year and time of day. Thus, regions with the lowest wind energy class may have considerably higher wind energy during part of the year and/or day. Conversely, regions with the highest wind energy may experience considerably lower mean wind energy throughout part of the year. Only a few areas of the world have potentially high wind energy throughout an entire year.

Most areas of the world have little or no wind data, and there is accordingly little data base regarding class or energy wind energy of the world. Of the large amounts of wind data available from specific areas at the time of preparation of the map, only a small proportion of the available data information on environmental height above ground level is in site exposure. Thus regional climatological information, upper air wind data and other appropriate information, where available, were used in the assessment.

1-75-100-10-10



# Mexico - Preliminary Wind Resource Map for Rural Power Applications



<sup>a</sup> Range of wind speeds are based on the Weibull k values of 1.25 to 3.0 found throughout the different regions of Mexico.

# *Future Developments of NREL Wind Mapping System*

- Perform additional validation studies
- Incorporate new climatic and land use data sets into mapping system
- Develop more sophisticated atmospheric mixing algorithms
- Explore new tools for advanced versions (e.g., mesoscale numerical models)

## *Program Accomplishments*

Unique world-class capability in wind resource assessment and mapping established at NREL through development and application of:

- Global data bases and analysis tools for producing reliable wind assessments, essentially anywhere in the world
- Sophisticated GIS-based mapping system for producing large-area high-resolution (1-km) wind maps